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A SUMMARY REPORT OF UNDERWATER
SOUND RANGE PREDICTION TECHNIQUES ✓

PART I - UNDERWATER SOUND RANGE PREDICTION BEFORE 1940

PART II - UNDERWATER SOUND RANGE PREDICTION FROM
OCTOBER 1940 TO FEBRUARY 1944

OCTOBER 12, 1962

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OCTOBER 12, 1962

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A SUMMARY ANALYSIS OF UNDERWATER SOUND RANGE PREDICTION TECHNIQUES

(Preliminary Edition)

ABSTRACT

↓
This preliminary edition is a documented historical summary of the underwater sound range prediction techniques utilized by the U. S. Navy through February 1944. It is the initial part of a complete summary analysis of all underwater sound range prediction techniques utilized by the U. S. Navy to the present.

For the period covered by the report, the significant developments in underwater sound range prediction are summarized, the sources responsible for the development are identified and the technical and operational considerations which dictated the changes are pointed out.

A bibliography of range prediction literature published during the periods of this report is included.
↑

A SUMMARY REPORT OF
UNDERWATER SOUND RANGE PREDICTION TECHNIQUES
(PRELIMINARY EDITION)

INTRODUCTION

This report is a chronological survey of sonar range prediction techniques. It consists of six parts. The first part is an outline of all the physical and chemical factors governing sound ranging. Each of the following four parts correspond to the four, (somewhat arbitrarily selected), chronological periods of the history of range prediction:

1. Before October 1940
2. October 1940 to February 1944
3. February 1944 to March 1959
4. March 1959 to present

In each period, the significant developments in underwater sound range prediction are summarized, the sources responsible for the development are identified, and the technical and operational considerations which dictated the changes are pointed out wherever they are known or can be discerned. The sixth part is a summary analysis and a discussion of the status of sonar range prediction art at the present time.

A bibliography of significant literature on sonar range prediction is included. Many of the references cited in this bibliography are not presently obtainable and hence their significance can only be estimated from the NDRC Division 6 Summary Technical Reports, the SAD Reports, and personal knowledge and experience.

I. A SUMMARY OF FACTORS GOVERNING SOUND RANGING

The major portion of Part I is taken from Wollard's manual, A Summary of Factors Governing Sound Ranges¹, written in 1944. Although the techniques of range prediction have changed somewhat during the past 18 years, Wollard's outline of factors governing sound range is still accurate and complete today.

"It is commonly observed that the maximum echo ranges on any vessel may vary from time to time by more than 3000 (sic) yards. This variation in range has been correlated with time of day and year, local weather conditions, depth, size or aspect of target and speed of A/SW vessel. It has been found that the best sound ranging conditions generally prevail during the winter months, in the morning, immediately after a storm, when the target is at periscope depth, and when the speed of the A/SW vessel does not exceed 15 knots (sic).

"Therefore, it is evident from these observations that any echo range is dependent upon a number of factors which may be divided into three groups: those related to (1) the A/SW vessel, (2) the transmitting medium, namely the water, and (3) the target.

...

"OUTLINE OF FACTORS GOVERNING SOUND RANGES

"I. Factors Related to the A/SW Vessel

A. Power Output and Efficiency of Sound Gear.

B. Self Noise from

1. Electrical noise inherent in sound apparatus.

¹G. P. Wollard, "A Summary of Factors Governing Sound Ranging," WHOI, June 1944.

2. Speed of ship a result of
 - a. cavitation noise from propellers, a function of
 - i. R.P.M. of propellers for a given hull speed.
 - ii. propeller design.
 - iii. propeller depth.
 - b. water noise from turbulence around projector head.
 - c. shielding by the hull between the propellers and the projector head which counteracts the effects of a. and b.
 3. Roll and pitch of vessel.
- C. Steadiness of vessel which controls
1. Water noise around projector head as a result of roll and pitch of ship.
 2. Tilting of projector head causing
 - a. variations in range of direct sound field.
 - b. variations in echo intensity.
 3. Quenching caused by the projector being carried up into surface layer of air bubbles by pitching of the ship.
- D. Depth of Projector Head which controls
1. Range of the direct sound field from the projector.
 2. Waternoise from surface waves.
 3. Quenching caused by the projector being brought into surface layer of air bubbles when vessel is pitching.
- E. Skill of Operator which determines
1. Doppler recognition.
 2. Recognition differential of echo against background noise.

✓ "II. Factors Related to the Water

(These factors will vary with geographic location, season of the year, time of day and local meteorological conditions.)

- A. Variations in the transmission velocity of sound affecting range of direct sound field and intensity distribution of sound in the direct sound field.

1. Horizontal variations resulting from changes in
 - a. temperature of the water
 - b. salinity of the water
 2. Vertical variations resulting from changes in
 - a. temperature of the water
 - b. salinity of the water
 - c. compression with increasing depth of water
 3. Velocity gradient in water layer in which projector is located
 4. Thickness of water layer having a constant velocity gradient in which the projector is located.
- B. Attenuation of sound intensity with range.
1. Divergence which varies with the velocity distribution with depth
 2. Absorption by
 - a. the mass of the water
 - b. the surface layer of air bubbles (varies with sea state)
 - c. the bottom (only important in shallow water over mud) (sic)
- C. Ambient noise in the water from
1. the surface (breaking waves)
 2. hydrophone effect of ships in the vicinity
 3. fish and shrimp noises in shallow water
- D. Reverberation from
1. the mass of the water
 2. the surface (pronounced when beam is bent upward as a result of increasing sound velocity with depth)
 3. the bottom (pronounced in shallow water over rough bottom, particularly when the beam is bent downward as a result of decreasing sound velocity with depth)
 4. deep scattering layers in the water (an occasional phenomenon)

E. Reflection from

1. the surface (important for extending range when the beam is bent upward)
2. the bottom (important for extending range in shallow water when the beam is bent downward) controlled by
 - a. bottom material
 - b. bottom roughness
 - c. bottom slope

F. Quenching as a result of

1. state of sea surface which governs roll and pitch of A/SW vessel
2. thickness of surface layer of air bubbles formed by breaking waves
3. depth of projector.

"III. Factors Related to the Target

A. Size, shape, draft and skin of hull

(These control the strength of the echo returned by the target and hence the range).

B. Depth of target determines

1. Maximum range possible when sound conditions are good
 - a. for targets above the thermocline (water layer with strong negative thermal gradient), the average maximum echo range is 3200 yards (sic).
 - b. for targets below the thermocline the average maximum echo range is 1400 yards (sic).
2. Hydrophone effect of submarine (the deeper the target the smaller the cavitation effect and hence noise at any speed).

3. Wake effect for recognition of aspect of submarine (increasing depth results in a decrease of the wake formed)
4. Masking effect of "knuckles" (elimination of wake with depth also eliminates the use of "knuckles")

C. Speed of Target determines

1. Doppler effect (change in sound frequency due to movement of target)
2. Strength of echo (a moving surface target produces a stronger echo than a stationary one)
3. Wake effect useful to
 - a. A/SW vessel in
 - i. recognizing aspect of target at periscope depth
 - ii. making contact at long range
 - b. submarine for evasive maneuvers
4. Listening range which is governed by
 - a. intensity of sound produced by target vessel
 - b. background noise level of listening vessel."

Section I of the preceding outline is easily modified to include the factors applicable to non-hull mounted sonar, such as VDS, or fixed sonar systems.

Following parts of this report will summarize the methods of incorporating the most important sound ranging factors into the various range prediction techniques, explain why some factors are neglected, and estimate the errors resulting from an incorrect accounting of important factors and the omission of less important ones.

II. UNDERWATER SOUND RANGE PREDICTION BEFORE OCTOBER 1940

During the 20 or more years preceding World War II, commercial and naval ships made an increasing use of instruments in which the transmission of sound through sea water played an important part. Throughout this period the engineers and physicists devoted most of their attention to the development of the instruments themselves, in anticipation of the practical gains that seemed likely through improvements in design and construction. Their anticipations, of course, proved to be correct; however, one important aspect of underwater sound transmission, the role played by the sea water, appears to have received little analytical attention by the sonar equipment developers during this period.

Some studies of the effects of the sea water were carried out at the Naval Research Laboratory during the period following World War I by Dr. Harvey Hayes and others. Unfortunately only limited references to these studies were found in currently available literature. In 1935 Stephenson published the first basic study of the effect of absorption, reflection and temperature gradients on underwater sound transmission¹. This was followed by two reports^{2,3} on absorption coefficients and by a report⁴ in which an attempt is made to correlate theory with the available experimental data on

¹E. B. Stephenson, "Transmission of Sound in Sea Water, Absorption and Reflection Coefficients and Temperature Gradients," S-1204, NRL, October 16, 1935.

²E. B. Stephenson, "Absorption Coefficients of Sound in Sea Water," S-1466, NRL, August 12, 1938.

³E. B. Stephenson, "Absorption Coefficients of Supersonic Sound in Open Sea Water," S-1549, NRL, August 2, 1939.

⁴E. B. Stephenson, "The Effect of Water Conditions on Propagation of Supersonic Underwater Sound," December 3, 1946.

underwater sound transmission. However, absorption data were so unreliable that data from different experiments differed by a factor of two or more. The U. S. Coast and Geodetic Survey also conducted a limited amount of work on sound transmission in sea water⁵.

But perhaps the most important development applicable to range prediction during this period was the development of the bathythermograph in 1938. As early as 1927, the British had compiled tables giving sound speed in sea water⁶ as a function of temperature, pressure and salinity; and improved tables were issued in 1939 by the British⁷ and by the Japanese⁸. These tables, used in conjunction with other bathymetric data, made possible the collection of underwater sound speed data on a large scale.

It should also be pointed out that the science of oceanography, upon which range prediction techniques were later to be based, reached a high stage of development during this period⁹. Indeed, the first range prediction techniques were formulated by combining aspects of the science of oceanography with some well known principles from physics. This will be discussed in the next section.

⁵O. W. Swainson, "Velocity and Ray Paths of Sound Waves in Sea Water," U.S. Coast and Geodetic Survey, 1936.

⁶"Tables of the Velocity of Sound in Pure Water and Sea Water for use in Echo-Ranging and Sound Ranging," British Admiralty Hydrographic Dept., H.D. No. 282, 1927.

⁷D. J. Matthews, Hydrographic Dept., British Admiralty, Report HD 282, Second Edition (1939).

⁸S. Kuwahara, Hydrographic Rev. 16, No. 2, 123 (1939).

⁹H. U. Sverdrup, M. W. Johnson and R. H. Fleming, "The Oceans," Prentice-Hall, Inc. (1942).

III. THE PERIOD OCTOBER 1940 TO FEBRUARY 1944

In October, 1940, the National Defense Research Committee requested the Woods Hole Oceanographic Institution to gather oceanographic information which might have a bearing on the detection of surface and underwater craft by sound ranging. On 1 February 1941, less than four months after initiation of this project, The Woods Hole Oceanographic Institution issued a report¹ surveying the problem of range prediction and containing the first underwater sound range prediction technique.

This Woods Hole report utilizes two fields of science in studying the transmission of sound in seawater: physics and oceanography. The physics of the problem was relatively well known, but this seems to be the first time that the oceanographic factors were considered in detail. The report discusses the speed of sound in sea water and the factors that determine it; and it clearly points out that the sound speed gradient, and not the absolute value of the sound speed, is of first importance in the horizontal range of underwater sound.

The report goes on to discuss the general theory of refraction and the effect of sound refraction in the near surface layers of the ocean. It then discusses the oceanography of the near surface layers with emphasis on those factors directly related to sound transmission.

The description of the range prediction technique contained in this first report is quoted below.

"PREDICTION OF THE MAXIMUM RANGE"²

"To predict the maximum range at which echoes may be obtained, it is necessary that the following items be known:

¹"Sound Transmission in Sea Water" (A Preliminary Report), Woods Hole Oceanographic Institution, February 1, 1941, PB 31049.

²Ibid.

- (a) The variation of velocity of sound with depth. In most cases the salinity is sufficiently constant to permit determination of the velocity distribution from thermal data alone. The thermal data may be obtained by use of the bathythermograph.
- (b) The power of the projector and the maximum sensitivity at which the receiving circuit may be operated. The power of the projector is perhaps best specified as the level of sonic energy in decibels db_0 in the direct beam at some distance R_0 small enough that refraction, surface reflection, etc. have not influenced the signal strength.
- (c) A graph showing the variation of signal strength with distance, constructed from the formula

$$db_1 = (db_0 + 20 \log R_0) - 20 \log R_1,$$

which assumes that geometrical divergence is the only factor influencing the signal strength.

- (d) Knowledge of the signal strength which must exist at the target in order that a measurable echo may be obtained for it. It is stated by Stephenson (NRL Report No. 3-1670, page 11) that 'for the equipment and technique used by the SEMMES and the S-20, the echo intensity from the S-20 on the surface was 60 ± 5 db below the level of the direct signal. At speeds under 12 knots, 0 db was the threshold level for 17 kc echoes on the SEMMES, so that at any time the direct signal received on the S-20 was 60 db or more, echoes from the S-20 on the surface could be heard on the SEMMES.'

"It seems likely that experiments with projectors of different power and with targets of different effective reflecting areas would show that this limiting value is different from 60 db in some cases,

but until further data are available this value will be adopted. A given target may be considered to act as a source of sound whose power depends on the product of the effective reflecting area times the strength of the direct signal at the target.

- (e) A ray diagram constructed from the thermal data according to the methods given in this Report.

The procedure for predicting the range is as follows:

- (a) Note the range at which the 60 db level (or a revised value of the limiting level in case this is available) is reached on the geometrical divergence curve. If no shadow zones are shown on the ray diagram inside this range, take it as the limiting range.
- (b) If there is a shadow zone, shown on the ray diagram, take range to be the edge of the shadow zone (for the target depth in question) plus an increase of a certain percentage of this range which is added to take account of the spread of sound into the shadow zone through diffraction, surface reflection, and bottom reflection. These percentages are as yet undetermined, but every test of the maximum range of echoes will help to determine them.

"It is hoped that experiments will be made in the near future which will make it possible to give more definite statements about the points which are left indefinite in the above paragraphs."

It should be noted that this range prediction technique is based upon the following assumptions:

- (1) The sound path may be described by ray acoustics.
- (2) The loss in intensity is a result of geometric divergence alone.
- (3) A signal will be returned from any target within the -60 db contours of the geometrical divergence curve.
- (4) The predictions are made for deep water; i.e. they do not consider bottom effects.

Reflection, diffraction, scattering and absorption of sound are discussed qualitatively in the report; however, no attempt is made to include these factors into the prediction of sound ranges.

This first range prediction technique was considered speculative at the time of its development, as there was no direct experimental verification of its validity. It was, however, to prove remarkably accurate; for it accounted, at least approximately, for the most important single factor influencing sound ranges - the sound speed gradient.

In June of 1941, an Oceanographic Division of the University of California Division of War Research was established at the U.S. Navy Radio and Sound Laboratory, San Diego, California. This organization collaborated closely with the Woods Hole Oceanographic Institution until the end of World War II.

In July 1941 a small number of experimental observations of range prediction were made off Key West, Florida³, providing perhaps the first direct corroboration of the theory given in reference (1). Osgood⁴ reports that observed maximum range agreed with the predicted maximum range to within 20%. The number of observations was not very large, however; and the error of $\pm 20\%$ was probably too small, as later experiments would indicate an error of about $\pm 33\%$.

Reference (4), written in March 1942, surveys the progress made on the range prediction problem up to that time. It goes over much the same ground as the first Woods Hole report in

³"Echo Ranging Experiments at Key West," July 23-30, 1941. Maurice Ewing (Woods Hole Oceanographic Institution).

⁴"Underwater Sound Fields," T.H. Osgood, March 28, 1942, Columbia University Division of War Research.

discussing the general principles of underwater sound transmission, and also discusses the corroborating experiments made at Key West and intensity measurements made by the Oceanographic Division of the University of California.⁵

The University of California intensity experiments were made with explosive caps, which generate waves of all frequencies. The results, however, were analyzed assuming only supersonic frequencies. The experiments indicated that the inverse square law was quite inadequate for calculating the intensity of the underwater sound fields and that, except for a thin region near the surface, the actual intensity in the sound field is less than that computed from the inverse square law. Osgood considered these discrepancies to be due to diffraction of the low frequency components of the sound from the explosive cap, to the attenuation of the high frequency components, and to the neglect of reflection from the surface.

The range prediction work completed in March 1942 was summerized as follows:⁶

- "(a) The laws which govern the propagation of sound in sea water are now fairly well known, so that, if certain oceanographic information is available at the particular time and place to which it applies, then the maximum echo range can be predicted, and the nature of the "sound field" under the sea can be used to advantage by a submarine which seeks to avoid detection. Further, a pursuit vessel, if aware of these things, may exploit them to its advantage.
- (b) Data which the oceanographic institutions possess, are obtaining or can obtain are used to determine the average ranging conditions at a particular locality at a

⁵"Some Characteristics of the Sound Field in the Sea," Oceanographic Division, The University of California, March 13, 1942.

⁶Osgood, op. cit.

particular season of the year. On the basis of such information, charts can be drawn up (one of the North Atlantic for summer months is now completed) which show at a glance the average echo-ranging conditions to be expected. Such maps will be useful in planning the routes of convoys, which should naturally avoid those parts of the ocean where sound ranges are exceedingly short. Or they may be used to estimate the number of escort vessels needed on particular parts of a run. The maps will also be important in staff work in planning submarine operations, since submarines can obviously operate more safely in waters where sound ranging conditions are bad."

In June, 1942, Osgood issued a second report concerning range prediction.⁷ This report, based on the continuing progress being made by the two oceanographic laboratories, conveys the impression that the range prediction problem was understood with confidence for the first time. Sufficient experimental evidence was available to show that the techniques of range prediction were already fairly adequate, and to indicate what might be done to improve the techniques further.

The report gives a comparison of predicted and observed ranges obtained in tests made in the Pacific from August to November of 1941. The results indicated that the range prediction technique based on ray theory was capable of predicting ranges with an accuracy of $\pm 33\%$, and in most cases the error was considerably less than this.

It is also observed in this report that the skill of the observer has an important effect upon the observed range. Osgood states that this factor may account for 20% of the range error.

⁷"Sound Ranges Under the Sea," T.H. Osgood, Columbia University Division of War Research, June 1942.

In addition, the approximate nature of ray diagrams is discussed in some detail. It is pointed out that the distinction made between regions of sound and regions of shadow by a ray diagram is not wholly realistic, due to (a) the approximation of the bathythermograph trace by several straight lines, and (b) the surface reflection and diffraction of the sound. It is also shown that it is necessary to consider errors inherent in the bathythermograph, which determines temperatures with a root mean square error of about 0.1°F . Osgood constructs an example showing that a -0.1°F error at the surface and a $+0.1^{\circ}\text{F}$ error at 50 feet would produce a range prediction error of 1000 yards at 3000 yards.

Attenuation, surface reflection, bottom reflection and reverberation are also discussed. It was concluded that knowledge of these phenomena was insufficient to account for them properly at that time.

The following tabulation of progress made on the basis of oceanographic work is given:

- (a) Assured echo-ranges can be predicted with useful accuracy from a bathythermograph record in water deeper than 100 fathoms. If the depth of the target is known, the limiting range may also be computed.
- (b) Positions of greatest safety for an attacking submarine can be predicted when the temperature distribution is known.
- (c) Maps of general sound ranging conditions have been prepared. More can be provided as required.
- (d) Slide rules have been devised to simplify range calculations.
- (e) A submarine bathythermograph has been designed and tested, and will soon be in production.
- (f) Maps of bottom conditions, particularly in coastal waters, are being made ready.

- (g) A velocity meter (for turbulence measurements in three dimensions) is being developed.

During the remainder of the 1940-1944 period, work proceeded in two directions: (1) the collection and analysis of experimental results with the aim of verifying and/or improving the existing range prediction technique and (2) the development of efficient procedures for the application of the technique at sea. Unfortunately no literature from the later part of this period is available; however, a thorough summary of the important parts of it are contained in a report (following) by The Columbia University Division of War Research.

In February and March 1944 new range prediction methods were adopted by the Navy. Reference 8 provides an historical survey of the reasons for the adoption of these new methods. This document is brief and yet gives a rather complete picture of the shortcomings of the older method and the reasons for adopting the new one; and marks an important step in the development of range prediction techniques. Consequently, the entire document is included as the final portion of this section.

NOTE: To avoid confusion references in this quoted CUDWR report are not footnoted but are appended on page 34.

⁸"Current Methods for Prediction of Maximum Sound Ranges, Columbia University Division of War Research, May 1, 1944.

"CURRENT METHODS FOR PREDICTION
OF MAXIMUM SOUND RANGES

(CUDWR Technical Memorandum #1, May 1, 1944)

PREFACE

"This memorandum provides an historical survey of the reasons for the range prediction methods adopted by the Navy in February and March 1944. The chief purpose of the discussion is to form a permanent record of how these range prediction methods were chosen. No elaborate attempt is made to justify these methods on the basis of all available data; this complete attempt to check the current doctrine by a comparison of observed and predicted ranges will be reported elsewhere¹⁹.

"In Section I the shortcomings of the previous range prediction methods are outlined. New methods for predicting Periscope-Depth Ranges are discussed in Section III, while Ranges at Depth are treated in Section IV.

"I. PREVIOUS METHODS OF RANGE PREDICTION

"Two manuals issued by the Navy in 1942-43 (References 1 and 2) contained range prediction methods based on the theory of refraction. These manuals, issued to surface vessels and submarines, gave simple tables for estimating from a bathythermograph slide the range from the echo-ranging projector to the shadow zone.

"This method was based on the following concepts: If the temperature-depth record is replaced by a series of straight lines, an accurate construction of a ray diagram (using one of several slide rules designed for the purpose - see Reference 3) will almost

always show a shadow zone; i.e., a region into which no sound ray penetrates. The range to the shadow zone at some particular depth is called the Limiting Range, and the Assured Range was, in this earlier method, defined as the least value of the Limiting Range. The range prediction method used in References 1 and 2 assumed that an echo can usually be received from a submarine which is not in a shadow zone. The tables used were regarded as a compromise with "slide-rule accuracy," adopted for the sake of simplicity, and designed to give rapidly an approximate value of the Assured Range in a variety of simple situations. The general evidence underlying this method was discussed in Reference 4.

"This early method had the following disadvantages:

"a. The Method was Incomplete. The simple tables were applicable to certain idealized situations. While these covered perhaps a majority of temperature distributions found in practice, there were many observed distributions for which no instructions were given. This was naturally a handicap to the practical use of bathythermograph information.

"b. The Predicted Ranges Were in Some Cases Much Too Long. Ranges obtained by the USS SEMMES, echo ranging at slow speed and with the best modern equipment on a new-construction submarine at various depths, illustrate this point. In isothermal water 160 feet thick, the Assured Range predicted from References 1 and 2 is 3000 yards, while the range on a submarine at periscope depth is about 6000 yards. The actual range obtained on a submarine in isothermal water of this thickness was about 3200 yards. However, when the submarine submerged into the thermocline below the isothermal layer, the maximum range at which echoes could be obtained dropped to about 1500 yards. In both cases the observed ranges were about one half of the predicted values. These tests alone made some revision of range prediction methods imperative.

The British had previously noted the marked drop in echo range when a submarine submerged through a density layer, and called this phenomenon Layer Effect (Reference 5). In addition, a statistical analysis of anti-submarine attacks (Reference 6) shows that ranges of first contact obtained on enemy submarines, even in areas where good sound conditions are to be expected, are rarely greater than 3000 yards. The conclusion may be drawn that present echo-ranging gear is usually not capable of obtaining an echo all the way out to the Limiting Range.

"c. Sound Transmission Runs Show in Some Cases No Correlation Between the Ray Diagram and Measured Intensities. When sharp downward refraction is present at the surface, recent transmission runs made at San Diego (reported in a preliminary way in Reference 7) indicate that the sound beam is bent sharply downward from the surface, leaving a shadow zone in which the sound intensity is enormously weakened. Measurements also indicate a drop in intensity at close ranges corresponding to the inner shadow zone discussed in References 1 and 2, giving rise to loss of contact at short ranges. However, these are the only two situations in which transmission data indicate the presence of shadow zones. In particular, when isothermal water is present over a thermocline, transmission runs in the isothermal layer show a gradual attenuation of sound, which proceeds at the same rate both in the direct sound field and in the predicted shadow zone, with no break apparent in the vicinity of the shadow boundary. This result is perhaps due to the presence of surface-reflected sound, perhaps to small-angle bending of sound rays produced by thermal microstructure. In any case, it indicates that the calculated Limiting Ranges for this situation are not particularly useful as an indication of maximum ranges obtainable in practice. Similar transmission runs made with receiving hydrophones below the thermocline show also a smooth attenuation of sound which seems to be independent of whether or not the receiving

hydrophone is in a computed shadow zone, and which shows no drop at the theoretical shadow boundary. Though the method by which sound penetrates the shadow zones has not yet been thoroughly explained, the transmission data indicate clearly that no reliance can be placed on the computed limiting range for the case of isothermal water overlying a sharp thermocline.

"d. Inadequate Emphasis was Placed on the Variability of Weak Temperature Gradients. In addition to the uncertain accuracy of range predictions when the temperature gradients are weak, recent evidence has shown that these small temperature gradients are extremely variable. In particular, in most transmission runs at San Diego the measured temperature distribution at one end of the run would usually be different from that at the other end, and if the bathythermograph slide at the beginning of the run showed mild downward refraction, another slide less than an hour later would frequently show either a sound channel or marked downward refraction. Since bathythermograph slides will not in practice be taken as often as once every hour, the exact prediction even of Limiting Ranges under such circumstances is out of the question.

"II. PRINCIPLES OF NEW RANGE-PREDICTION METHODS

"The discussion in Section I indicates that the Limiting Range is not a good indication of the maximum echo range when an isothermal layer overlies a sharp negative gradient. Analysis of the echo-ranging trials by the USS SEMMES on the submarine DARTER (see Reference 8) showed that when the submarine was at the maximum range the sound intensity at the target, computed from the refraction theory alone, and neglecting attenuation (and surface reflection), varied between 70 and 73 db below the intensity one yard from the projector.* Echo-ranging runs on three other submarines gave similar results. This suggested that the 70 db contour predicted from the simple refraction theory might be a generally useful guide to maximum echo ranges. The following arguments make this rule-of-thumb seem plausible.

"A more detailed analysis of the problem of maximum echo ranges (see Reference 9) indicated that the actual sound intensity at the target at maximum range should depend on the background sound tending to mask the echo. It is not the echo level which is constant at the maximum ranges found in different runs, but rather the difference between echo level and background level. This background can be noise, produced by the motion of the ship and echo-ranging projector through the water. Or it can be reverberation, consisting of false echoes from irregularities in the water or at the surface and bottom. The noise level is independent of the target range, while the reverberation level decreases with increasing range and finally falls below the noise level (somewhere between 2000 and 3000 yards, under most conditions). The strength of a hypothetical echo which could just be detected, therefore,

*The maximum ranges for "solid echoes" both above and below the thermocline lay between the -66 and the -69 db refraction contours.

decreases with increasing range, until it becomes constant at those ranges where reverberation is below noise. The sound intensity at the target necessary to produce this just detectable hypothetical echo decreases correspondingly as the range to the target increases, remaining constant beyond the range where noise and reverberation are equal.

"Furthermore, transmission runs show that the sound intensity is attenuated exponentially a certain number of db per kiloyard, in addition to the weakening predicted by the simple geometrical refraction theory. The constant of attenuation is apparently variable, but between 3 and 4 db per kiloyard seemed the most reasonable value to assume at the time the new methods of range prediction were adopted. As a result of this attenuation, the echo intensity actually decreases more rapidly with increasing range than the simple geometrical ray theory would indicate. If a target at 1500 yards moves out to 3000 yards this additional decrease of echo intensity is between 9 and 12 db, which is superimposed on a decrease of 12 db arising from the divergence of the sound.

"In the SEMMES tests, the change of background with range between 1500 and 3000 yards was about the same as the additional change of echo intensity produced by attenuation. Power level records made during the runs showed that at 3000 yards the reverberation was below the noise level, while at 1500 yards the reverberation in deep water was 5 to 12 db above the noise level, the value varying as the ship speed varied from 5 to 15 knots. Thus the background diminished by 5 to 12 db as the range increased from 1500 to 3000 yards. This may be compared to an additional decrease between 9 and 12 db in echo intensity resulting from the assumed attenuation of 3 to 4 db per kiloyard of sound travel (6 to 8 db per kiloyard of range). Thus, if the echo level were computed on the basis of spread alone, and the noise level taken as the background level at any range (thus neglecting

reverberation) the computed echo-background ratios should not depart very much from the true echo-background ratios, at least at ranges between 1500 and 3000 yards under the conditions of these tests. This argument helps to explain why the targets at maximum range were invariably found to lie near the -70 db contour computed from spread alone, for good and bad sound conditions alike. The actual intensity drop between 1 yard and maximum range depends, of course, on the value of the range; i.e., on the distance over which attenuation is operative. The actual transmission loss was about 80 db for long ranges, and about 75 db for ranges of 1500 yards.

"Insufficient data were available to indicate how generally the effect of reverberation would be quantitatively so similar to the effect of attenuation. They can be assumed to balance, on the basis of the SEMMES data, only for ranges between 1500 and 3000 yards. For practical purposes, this limitation is not very important. Very short ranges are predicted only when strong temperature gradients at the surface bend the sound beam downwards and give rise to a sharp shadow boundary, where the intensity contours are crowded so close together that the actual contour used for range predictions is relatively unimportant. Ranges over 3000 yards occur seldom, and are not predicted in the present methods; to predict these it would be necessary to consider the actual sound intensity necessary at maximum range, and to take attenuation into account. As a result of these considerations, it was believed that for most situations computing the echo-background ratio considering only spread and noise would not lead to serious error.

"Preliminary examination of the Woods Hole reverberation records made with Power Level Recorders connected to standard Navy gear in routine operation, indicates that the reverberation

and noise levels observed on the SEMMES are probably fairly typical. In particular, the drop in the background level between 1500 and 3000 yards is usually about 10 db in deep water. The absolute background levels are less certain. Fortunately a relatively wide variation in these levels is possible without a very serious change in maximum range, owing to the rapid change of echo intensity with range near maximum range (see Reference 10, where a discussion of the accuracy of the new range-prediction methods is reported). For instance, if a submarine is in an isothermal layer extending up to the surface, an increase of 5 db in the background noise level will decrease the maximum range by not more than about 20 percent in a typical case.

"This quantitative discussion of power-level records is of course not conclusive, since the recognition differential is probably quite different for reverberation and for noise. If the Power-Level recorder shows that reverberation at 1500 yards is 5 db above the noise level at 3000 yards (measured in a band roughly 1000 cycles wide) the intensity of a just detectable echo at 1500 yards may be as much as 10 db higher than at 3000 yards. Reverberation is more variable than background noise, and is also concentrated in the same frequencies as the echo (unless strong Doppler effect is present); thus reverberation is more effective than background noise in masking an echo. The important fact is that the maximum range observed in these SEMMES tests coincided so closely with the -70 db contour. The quantitative measurements are cited simply to indicate that this result is not unreasonable on the basis of present theory, and that similar results may be expected in normal operation of standard Navy equipment.

Since new range prediction methods were urgently required for the summer of 1944, and since time did not permit the accumulation of the additional data required for a more complete analysis of the problem, it was therefore decided to base the new predictions on the range to the -70 db contour computed from divergence alone. It was believed that this method, which was known to give correct results for the SEMMES echo-ranging trials, would be usefully accurate in most situations.

"III. PREDICTION OF MAXIMUM RANGE ON A SUBMARINE AT PERISCOPE DEPTH

"Under (a) through (e) below are discussed methods for predicting Periscope-Depth Ranges for each of the five "patterns" used for classifying bathythermograph slides. Instructions for determining the range pattern are given on Page 15 of the new surface vessel manual (Reference 11). The predictions given in the revised submarine manual (Reference 12) do not utilize range patterns, but are essentially equivalent to the rules in the surface vessel manual. The discussion in this memorandum covers only the major issues; minor changes made to simplify the prediction methods or the Sonar Message, or for various other purposes are not mentioned. Also, a very large number of variants of these methods were discussed at various times, and are not treated here.

"a. Pattern MIKE (Mixed Layer). This includes all situations where a layer of nearly constant temperature is present at the surface with a thermocline present at some depth below 30 feet. This class also includes the case where temperature is constant at all depths. The large and unexplained variation of attenuation observed in sound transmission runs for this pattern made at San Diego made exact prediction of Periscope-Depth Ranges impossible. As an example of this variation, ranges to the true -80 db contour, as measured in the San Diego Transmission runs, are shown in Figure 1. Since no precise predictions were made from these data no attempt was made to compute the position of the -70 db contour in the absence of attenuation; however, for ranges of about 3000 yards this will coincide with the observed -80 db contour.

It is evident from this Figure that if the isothermal layer is 50 feet deep or more, the maximum echo range is almost always greater than 2000 yards. If the depth of the isothermal layer is between 30 feet and 50 feet, the maximum range will be greater than a thousand yards, and may exceed 2000 yards. There is also some correlation with depths of the isothermal layer greater than 50 feet, but the scatter is very great.

In view of this large scatter all MIKE patterns were grouped together in the new surface vessel manual (Reference 11), and a LONG Periscope-Depth Range predicted. In the rules for checking the operating condition of the equipment by observations of the maximum range on a large surface vessel, instructions were given that ranges greater than 2500 yards should be obtained with isothermal layers 50 feet or more deep. In the submarine manual (Reference 12), maximum echo ranges for shallow isothermal layers (50 feet or less) were predicted as 1500 to 3000 yards, while for a submarine above a deeper layer, ranges of 2000 to 3500 yards were predicted. It should be pointed out that the values plotted in Figure 2 are not all those which are now available but are restricted to the ones which were examined at the time that the range prediction methods were being decided on. Comparison of this and other figures with the more recent ones in Reference 13 will show the additional points obtained.

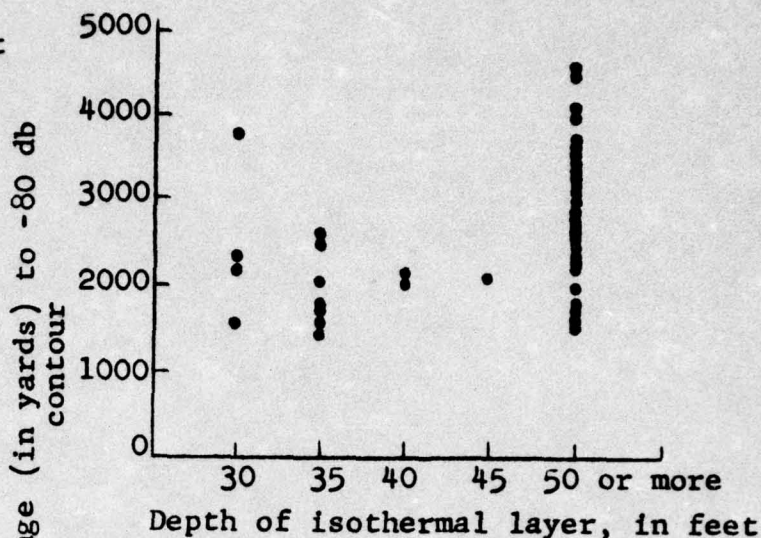


FIGURE 1

"With strong winds maximum echo ranges noted in A/S operational reports from the North Atlantic are found to be less than with weaker winds. British and American data were analyzed in Reference 14; the average values found were subsequently somewhat increased - see Reference 15. While the effect of winds on sound-ranging conditions is certainly different for different vessels under different operating conditions, and may be different for different sea states, the values adopted are believed to represent in a general way the typical effects to be expected.

"b. Pattern CHARLIE (Changing). Pattern CHARLIE includes all cases where the difference of temperature between the surface and 30 feet is greater than 0.3° , but is equal to or less than $1/100$ of the surface temperature. The lower limit was chosen to be close to the limit of accuracy of reading the bathythermograph slide under most service conditions. The upper limit corresponds to a Limiting Range of 1000 yards. When the surface temperature gradient falls within these limits, the sound transmission data are intermediate between those for MIKE and NAN, with some runs showing uniform attenuation at all ranges, and others showing a sharp break in slope at the computed shadow boundary. In addition, the variability of temperature conditions over a period of 3 to 4 hours is believed to be high. Only a few sound transmission runs were made under this condition, but the available data indicate that the observed distribution of Periscope-Depth Ranges is between 800 and 2000 yards. Periscope-Depth Ranges for all these patterns are classified as MEDIUM in the surface manual; i.e., between 1000 and 2000 yards (Reference 11). In the submarine manual (Reference 12), the maximum range is about 1500 yards, as indicated in Rule 4 for a moderately strong temperature gradient, and between 1500 and 2000 yards in Rule 2 for a weaker temperature gradient.

c. Pattern NAN (Negative Gradient). This pattern includes cases in which the temperature difference from the surface to 30 feet is greater than $1/100$ of the surface temperature. (Exception: When the temperature difference from 15 to 50 feet is 0.2° or less, a sound channel may be present and the pattern is CHARLIE rather than NAN.) With this pattern, transmission curves usually show a sharp break in slope somewhere in the vicinity of the computed shadow boundary; the sound intensity well inside the shadow zone is usually some 30 db below the corresponding intensity in the direct sound field at the same range.

In Figure 2 are plotted the observed ranges to the true -70 db contour against the ranges found from the old tables in References 1 and 2 (approximately the Limiting Ranges). In accordance with the discussion in Section II, these values should be corrected for an assumed attenuation to give ranges to a refraction contour in the absence of attenuation. At these short ranges this correction is small and may be neglected, especially since the intensity contours are close together at the boundary of the shadow zone.

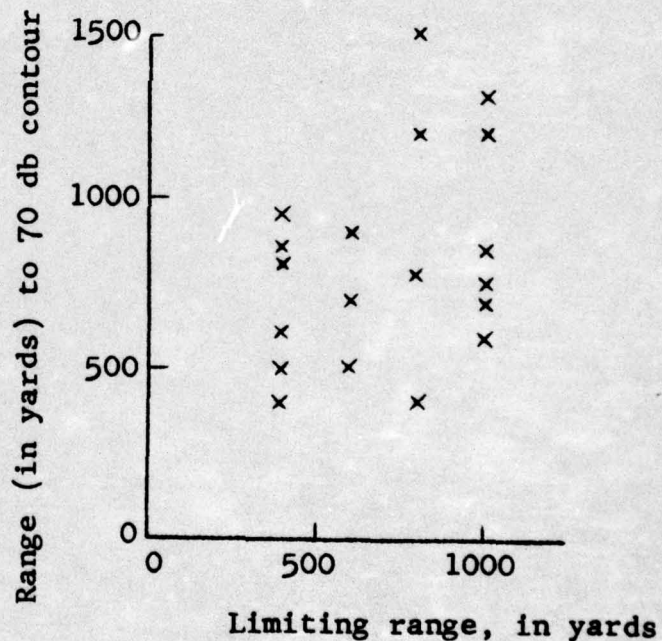


FIGURE 2

It will be seen from the Figure that the ranges determined from the transmission data are somewhat longer than predicted from the simple tables. In addition the scatter is very large. Accordingly, in the surface vessel manual all NAN ranges at periscope depth are predicted as SHORT. In the submarine manual, however, Rule 4 distinguished between moderately sharp gradients and very sharp gradients, with 800 to 1000 yards for gradients of 1° to 2° in the first 30 feet (these gradients give maximum ranges between 400 and 800 yards in the old method), and 500 yards predicted for a gradient of 5° in the top 30 feet, (corresponding to 300 yards in the former rules).

"d. Pattern PETER (Positive Gradient). This pattern includes all cases where the temperature at some depth below the projector is greater than the temperature at the projector. No observational data obtained with directional sources are available for pattern PETER. It seems theoretically reasonable that surface reflected sound will give echoes at long ranges, even when the Limiting Range for the direct sound in the surface layer is moderately short. In any case strong positive gradients are usually well below 30 feet, with isothermal water likely above. Accordingly, LONG Periscope-Depth Ranges (greater than 2000 yards) were predicted for this pattern, except when strong winds are present. Range Predictions for winds Force 6 - 7 are the same as for pattern MIKE.

"e. Pattern BAKER (Bottom Reflection). This pattern includes all situations where the water is less than 100 fathoms deep, and the bottom is not MUD. (Exception: Where very sharp positive gradients bend most of the sound beam back to the surface and make bottom reflections unimportant, the pattern is PETER regardless of the depth of the water). No definite predictions were made for pattern BAKER, owing to the lack of definite quantitative information both on sound transmission and on reverberation in shallow water. However, in the submarine manual (Reference 12), certain conservative rules were given on the basis of general qualitative information.

"IV. PREDICTION OF MAXIMUM RANGES ON A SUBMARINE AT DEPTH

"Under (a) through (e) below, range prediction methods giving the "Range at Depth" for each pattern are discussed. For patterns MIKE, CHARLIE, and PETER, this range is equal to the Assured Range; i.e., the range on a submarine at the best depth for avoiding detection. For pattern NAN, however, the maximum range is least near the surface, and the Periscope-Depth Range equals the Assured Range; for this pattern the range at 300 feet is sent for the Range at Depth.

"a. Pattern MIKE (Mixed Layer). Predictions of range below the thermocline were based essentially on sound intensity calculations carried out at Woods Hole and San Diego (References 16 and 17); this work analyzed the geometrical divergence of rays passing through the thermocline. For practical predictions under a wide variety of conditions, an analysis was made of the change of intensity above and below a temperature discontinuity. The formula resulting from this straightforward analysis was reported in Reference 18, and on this basis tables of ranges to the -70 db contour were constructed for different temperature discontinuities at different depths. To apply these results to continuous temperature gradients instead of discontinuities, it was necessary to determine the depth range H such that the temperature difference over this range produced the same decrease in intensity as the same temperature difference across a discontinuity. This quantity H , a function of depth, was determined empirically by an inspection of the numerical calculations for different patterns carried through at Woods Hole (see Reference 17). Subsequently it was discovered at San Diego that results of the same accuracy could be obtained by using a slightly modified table, and reading the temperature difference in the top 30 feet of the thermocline. Plausible rules for several gradients at different depths were adopted after these had been checked by a comparison with numerical intensity calculations made at San Diego - see Reference 16.

"In Figure 3 are shown the ranges computed from the final table adopted, compared with ranges determined from San Diego sound transmission runs made with the hydrophone below a thermocline. These "measured ranges" are ranges to the -70 db refraction contour, found by correcting the observed intensities for an assumed attenuation of 3 db per kiloyard. A similar plot results if 4 db per kiloyard is used. The circles refer to MIKE patterns; the other points are discussed below. While the scatter is large, a general correlation is evident; almost all the points lie within or very close to the limits of accuracy claimed; i.e., within $2/3$ to $4/3$ the predicted values.

"The change of range with increasing depth below the thermocline is discussed in the Appendix to the surface vessel manual (Reference 11) and on pages 12 and 13 of the submarine manual (Reference 12). The rules given are based partly on a first order theory giving the change of intensity with depth below a temperature discontinuity, and partly on an examination of the intensity contours computed at Woods Hole for different temperature gradients (Reference 17). No comparison of these rules with observational data was possible.

"b. Pattern CHARLIE (Changing). Theory indicates that when weak temperature gradients are present in the top 30 feet, the angle at which sound rays enter the thermocline is greater than in isothermal water, and Layer Effect is somewhat diminished. The Table used for MIKE patterns was modified slightly according to some theoretical calculations made at San Diego, and is used in the surface vessel manual for all CHARLIE patterns. In the submarine manual, the table used is a compromise between the MIKE and CHARLIE tables. Since the table gives Assured Ranges for all cases where a negative gradient is present, and positive gradients are unimportant, Periscope-Depth Ranges for NAN and CHARLIE patterns are also included in the top row of this table. The dots plotted in Figure 4 were computed from the CHARLIE table in the surface vessel manual.

"c. Pattern NAN (Negative Gradient). For this pattern the Limiting Range at 300 feet is tabulated in the surface vessel manual. The assumption is made that the measured temperature difference from 30 to 300 feet occurs in a uniform gradient over the entire depth interval. If this temperature drop occurs below 150 feet, the actual Limiting Range will be considerably greater than the value computed. However, in this case the range at 300 feet will then be reduced by Layer Effect. Examination of the ranges below temperature layers predicted for patterns MIKE and CHARLIE shows that the range in this latter case will be reduced to about the same value found from the Limiting Range table, used for NAN patterns.

"A comparison between the ranges predicted for pattern NAN and those found from the Sound Field data is shown by the crosses in Figure 4. The points plotted are not all at 300 feet. The computed ranges were found from a more general table, similar to the one adopted, but giving Limiting Ranges at different depths for NAN patterns. (The dividing line between NAN and CHARLIE used in Figure 4 is not exactly the same as was finally adopted, but the difference is small).

"d. Pattern PETER (Positive Gradient). The lack of observational data for this pattern makes range predictions on targets below the positive gradient rather uncertain. The refraction theory predicts shadow zones as close as 200 yards to the projector in many situations; these ranges were arbitrarily increased to about 500 yards. The final Table for Range at Depth represents a compromise between the values found for a linear positive gradient, extending from the surface to the depth of maximum temperature, and those for a discontinuous sharp increase of temperature. In addition, in the surface vessel manual, values above 2000 yards were reduced to less than 2000 yards to save the additional complexity of considering Force 6 and 7 winds.

"e. Pattern BAKER (Bottom Reflection). No prediction of Range at Depth is made for this pattern.

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OF MAXIMUM SOUND RANGES**

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